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Reason for high strength and good ductility in dual phase steels composed of soft ferrite and hard martensite

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Reason for high strength and good ductility in dual phase steels composed of soft ferrite and hard martensite

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Abstract. Dual phase (DP) steels in which the microstructures are composed of a soft ferrite phase and a hard martensite phase are known to show good strain-hardening, high strength and large elongation, but reasons for their superior mechanical properties are still unclear. In the present study, two types of DP structures, having either networked martensite or isolated martensite were fabricated in a low-carbon steel by different heat treatment routes, and their tensile deformation behavior was analyzed using the digital image correlation (DIC) technique. It was revealed that the DP specimens having networked martensite microstructures showed a better strength-ductility balance than the DP specimens with isolated martensite structures. The microscopic DIC analysis of identical areas showed that the strain distribution within the DP microstructures was not uniform and the plastic strain was localized in soft ferrite grains. The strain localized regions tended to detour around hard martensite but eventually propagated across the martensite. It was found also from the DIC analysis that the degree of strain partitioning between ferrite and martensite in the networked DP structure was lower than that in the isolated DP structure. The deformation became more homogeneous when the hard phase (martensite) was connected to form a network structure, which could be one of the reasons for the better strength-ductility balance in the networked DP structure compared to that in the isolated DP structure.

1. Introduction

Demands on high strength steels have been increasing more and more in recent years, based on two different requirements from our society. One requirement is to reduce the weight of transportation equipment thereby saving fossil fuels and reducing greenhouse gases. The other is to increase the safety of equipment and constructions in case of accidents such as collisions, and earthquakes. These two demands are conflicting, but strengthening of materials used for equipment and constructions is one of the promising solutions. In the field of automobile steels, for example, so-called advanced high strength steels (AHSS) have been energetically studied and developed [1]. One of the important AHSS is a dual phase (DP) steel in which the microstructure is composed of the soft phase (ferrite) and the hard phase (martensite or/and bainite). DP steels show good strain hardening ability, resulting in high tensile strength, good yield ratio, and fairly large tensile elongation. On the other hand, the



exact reasons for the superior mechanical properties of DP steels are still unclear. One may say that the hard phase brings about high strength and soft phase gives large ductility, but this is not a scientific explanation. Since the microstructures of DP steels are micro-scale mixtures of ferrite and martensite, mechanical interactions between the soft and hard phases must be clarified for fundamentally understanding their good mechanical properties.

There are various microstructural parameters that can influence the deformation behavior of DP steels, namely, the volume fraction, size, hardness ratio, and distribution of the two phases [2-7]. In the present study, two different types of DP microstructures composed of soft ferrite and hard martensite are fabricated by different heat treatment routes in a low carbon steel. One type of microstructure has a networked martensite, while the other type has isolated martensite in the microstructure. For understanding the mechanical interaction between ferrite and martensite, local deformation in the microstructures is quantitatively analyzed by means of the digital image correlation (DIC) technique [8].

2. Experimental Procedures

A low carbon steel having a chemical composition of Fe-0.087C-0.79Si-1.77Mn-0.009P-0.002S-0.02Cr-0.01Mo-0.003N (mass%) was used in the present study. DP microstructures in proeutectoid steels can generally be obtained through intercritical annealing at the ferrite + austenite two-phase temperature, followed by quenching, during which austenite transforms to martensite. When the phase structure prior to intercritical annealing changes, as is illustrated in figure 1, different types of DP microstructures having different distributions of martensite can be fabricated. In route I of figure 1 where a ferrite-based microstructure is intercritically annealed in low carbon steels, austenite preferentially forms along the ferrite grain boundaries (and on pearlite or cementite with small fractions), so that martensite obtained by quenching has a network structure. In route II, on the other hand, where the steel is firstly austenitized and then intercritically annealed, ferrite forms preferentially along grain boundaries of austenite, so that the martensite in the final DP microstructure is isolated. In the present study, some sheets 1 mm thick of the 0.087C-0.79Si-1.77Mn steel were firstly austenitized at 950°C for 1.8 ks and then air-cooled to room temperature to obtain a microstructure composed of ferrite and a small amount of pearlite (route I). The steel sheets with the ferrite-based microstructure were intercritically annealed in the ferrite + austenite two phase regions (760°C ~ 840°C) for 1.8 ks, followed by water-quenching to fabricate DP structures with a networked martensite. The other steel sheets were austenitized under the same condition as in route I (950°C, 1.8ks), then cooled down to temperatures from 720°C to 820°C, and intercritically annealed at the hold temperature for 1.8 ks, followed by water-quenching to obtain DP structures with isolated martensite (route II). All the heat treatments were carried out in a salt bath.

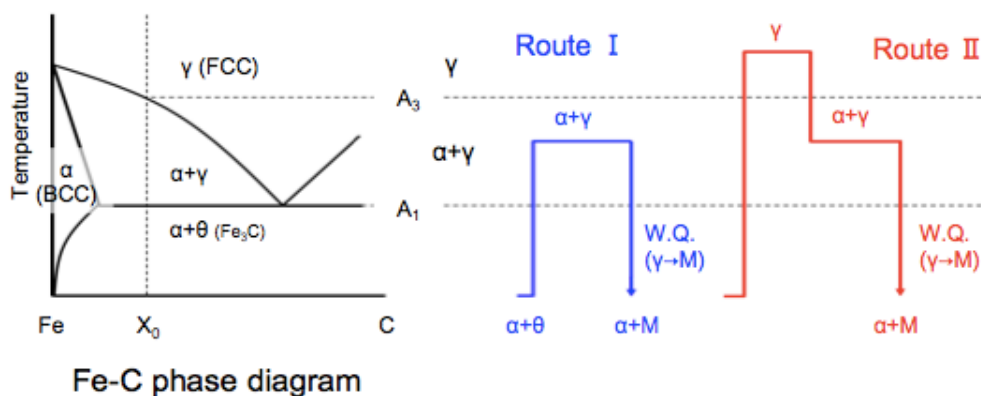


Figure 1. Schematic illustration of the Fe-C phase diagram and two kinds of heat-treatment route to obtain DP structures having different distribution morphologies of martensite.

Tensile specimens 5 mm in gage width, 10 mm in gage length and 1mm in thickness (1/5 of JIS-5 specimen) were cut from the heat-treated sheets. Tensile tests were conducted at room temperature at an initial strain rate of $8.3 \times 10^{-4} \text{ s}^{-1}$. Microstructures in identical areas in the specimens were observed by scanning electron microscopy (SEM) before and after tensile testing to various strains. Prior to the tensile test and SEM observation, the broad surfaces of the specimens were mechanically polished using emery papers and then electro-polished in a 10% perchloric acid (100ml HClO_4 + 900ml CH_3COOH) solution. The electro-polished specimens were etched using a 3% nital (30ml HNO_3 + 970ml $\text{C}_2\text{H}_5\text{OH}$) solution to reveal ferrite and martensite microstructures. The obtained SEM images of the identical areas were used as markers to track displacements of the same points in the microstructures. From the displacements of the markers (microstructural features), the two-dimensional strain tensor at each point in the microstructures was calculated, from which maps showing strain distributions in the microstructures were constructed.

3. Results and Discussion

Figure 2 shows SEM micrographs of the DP microstructures fabricated by heat treatment route I in figure 1. In the SEM micrographs, the ferrite is black, while martensite is seen as a white phase including substructures. In all micrographs of figure 2, networked martensite structures where martensite phase is connected to each other can be recognized. With increasing the intercritical annealing temperature, the volume fraction of austenite at the temperature increases, as is expected from the equilibrium phase diagram, so that the volume fraction of martensite (V_m) in the specimen after water-quenching increases. Mean grain sizes of ferrite (D_F) and martensite (D_M) are also indicated in figure 2, which are fairly fine and in the range from 2 μm to 5 μm .

Figure 3 shows SEM micrographs of the DP microstructures fabricated by heat treatment route II in figure 1. Different from figure 2, DP structures with isolated martensite are observed. The intercritical annealing temperatures shown in figure 3 were selected so as to have the volume fractions of martensite (V_m) similar to those of the DP structures with networked martensite shown in figure 2 (a-c). The volume fraction of martensite (V_m) increases with increasing the intercritical annealing temperature. The mean grain sizes of ferrite (D_F) are several micro-meters, although the mean grain sizes of martensite (i.e., the grain size of prior austenite) are larger than those in the network DP structures.

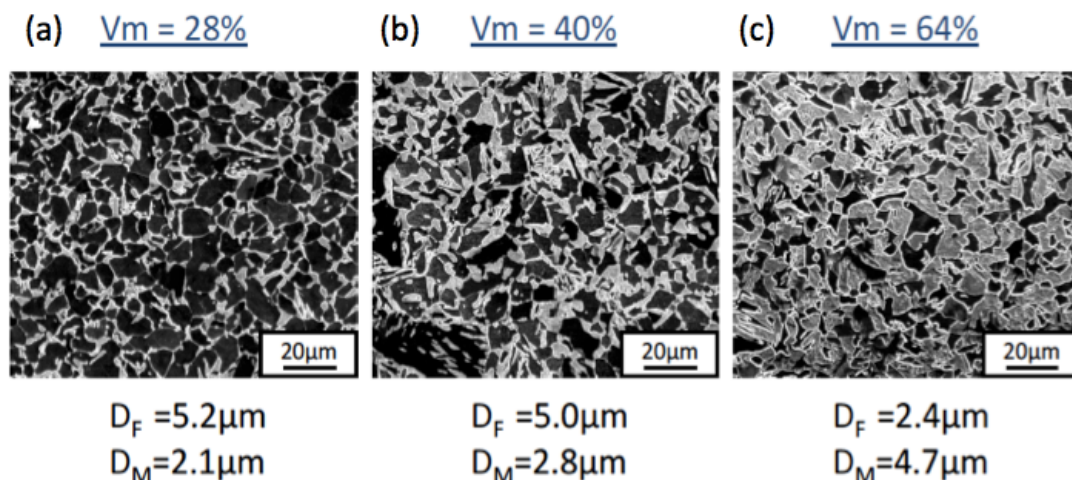


Figure 2. SEM microstructures of the DP specimens having networked martensite morphologies heat-treated using route I. Intercritically annealed at different temperatures: (a)

760°C; (b) 790°C; (c) 820°C. The volume fraction of martensite (V_m), mean grain size of ferrite (D_F) and mean grain size of martensite (D_M) are indicated.

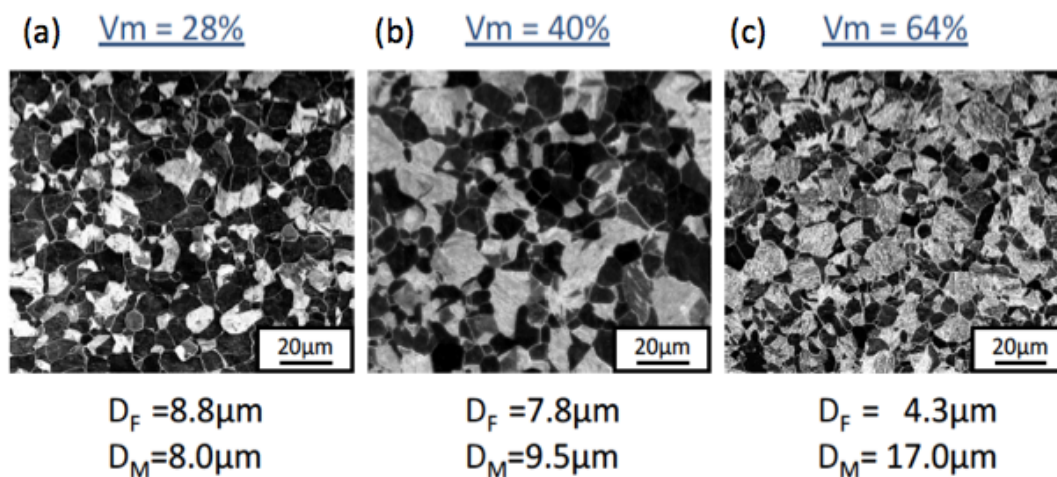


Figure 3. SEM microstructures of the DP specimens having isolated martensite morphologies heat-treated using route II. Intercritically annealed at different temperatures: (a) 740°C; (b) 760°C; (c) 780°C. The volume fraction of martensite (V_m), mean grain size of ferrite (D_F) and mean grain size of martensite (D_M) are indicated.

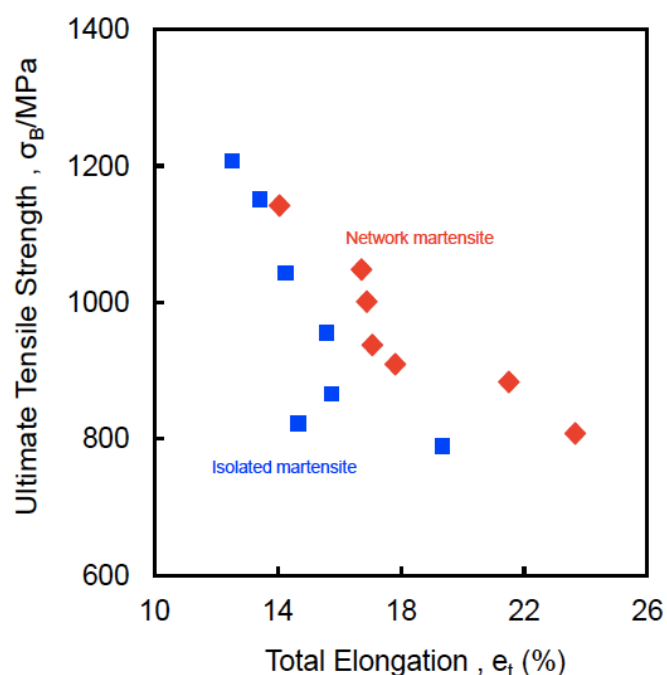


Figure 4. Ultimate tensile strength versus total elongation obtained from tensile tests showing the strength-ductility balance of the DP specimens with different volume fractions of martensite. Values of the DP specimens having networked martensite morphologies are plotted by red diamond symbols, while those of the isolated martensite specimens are plotted by blue square symbols.

Tensile tests of specimens having the two types of DP microstructures shown in figures 2 and 3 were conducted at room temperature. The obtained tensile strength and total elongation are plotted in figure 4. In both types of DP structures (with networked martensite or isolated martensite), the tensile strength decreases with increasing total elongation, which reflects a general trade-off balance between strength and ductility in most materials. However, it is noteworthy that the DP specimens having networked martensite show better strength-ductility balance than the DP structures having isolated martensite. To understand the reasons for the difference between the networked DP and the isolated DP, microscale DIC analysis was carried out for both types of DP structure.

Figure 5 shows SEM micrographs of an identical area in the specimen having the networked DP structure before the tensile test (a) and after deformation to various tensile strains (b-d). The volume fraction of martensite (V_m) in this specimen was 28%. With increasing the tensile strain, the microstructure gradually elongated along the horizontal direction, i.e., the tensile direction. Using those SEM microstructures, DIC analysis was conducted.

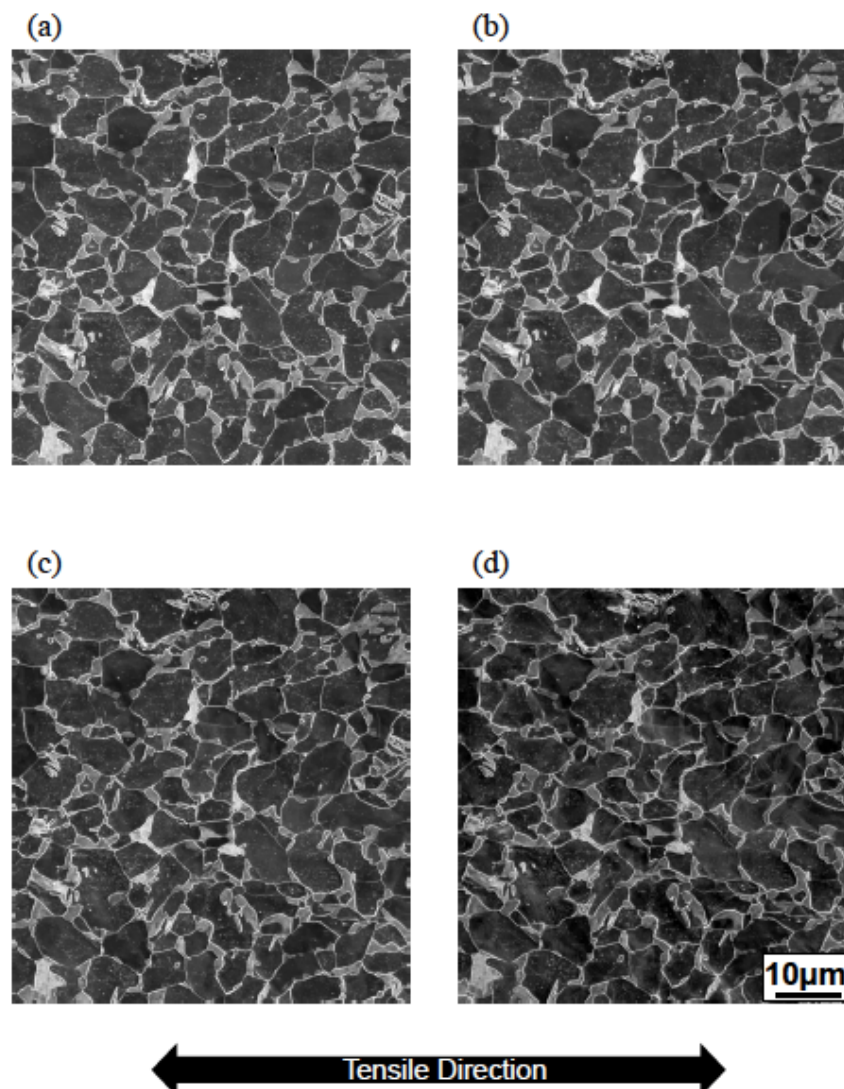


Figure 5. SEM microstructures of an identical area in the DP specimen having a networked martensite morphology. The volume fraction of martensite (V_m) was 28%. The specimen was deformed to various tensile strains: (a) before the tensile test; tensile tested to (b) 2.8%; (c) 6.5%; (d) 10.0% strain.

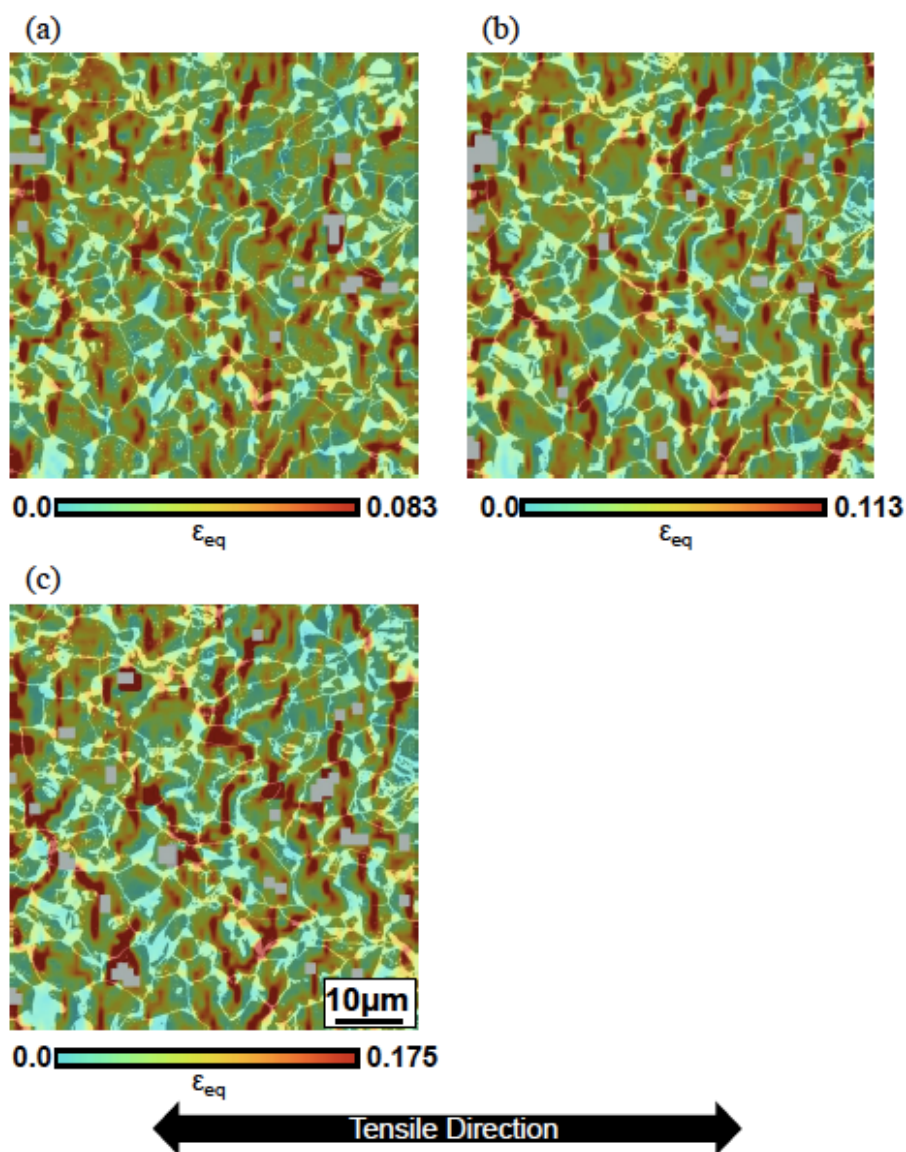


Figure 6. Local strain distribution maps obtained from the DIC analysis of the DP specimen having the networked martensite morphology. The volume fraction of martensite (V_m) was 28%. The specimen was deformed to various tensile strains: (a) tensile tested to 2.8% strain; (c) 6.5%; (d) 10.0%.

Local strain distributions obtained by the DIC analysis in the same area in the networked DP specimen deformed to three different tensile strains shown in figure 5 are plotted in figure 6. Color maps indicating the von Mises equivalent strain (ϵ_{eq}) at each point in the microstructure are superimposed on the DP micrographs where martensite and ferrite are drawn in white and black, respectively. The amount of the equivalent strain is quantitatively expressed by the colors according to the bars shown below each strain distribution map. As ferrite shows a fairly homogeneous contrast in the SEM images, it was sometimes difficult to track the positions, especially at center regions, of relatively coarse ferrite grains in the DIC analysis. Such uncertain regions are shown in gray in the strain distribution maps. The strain distribution within the DP microstructure was not uniform but

rather was localized even at small tensile strains. The strain-localized regions, indicated by yellow to red colors are mainly located within soft ferrite grains and tend to propagate across the hard martensite at higher strains. It should be noted that the DIC analysis was reset after each strain, so that the strain distributions in figure 6 (b) and (c) are those within the tensile deformation ranges from 2.8% to 6.5%, and from 6.5% to 10.0%, respectively. Nevertheless, it is interesting that the strain localized regions are observed at the same positions in figure 6 (a), (b) and (c).

Figure 7 shows strain distribution maps in the same area of a specimen having the isolated DP structure. The volume fraction of martensite (V_m) of this specimen was same as that of figures 5 and 6, 28%. The distributions of von Mises equivalent strain are again not uniform but are localized mainly in the soft ferrite regions. Although the strain localized bands tended to be connected at higher strains, it is clear in figure 7 that the strain localized bands detoured around hard martensite.

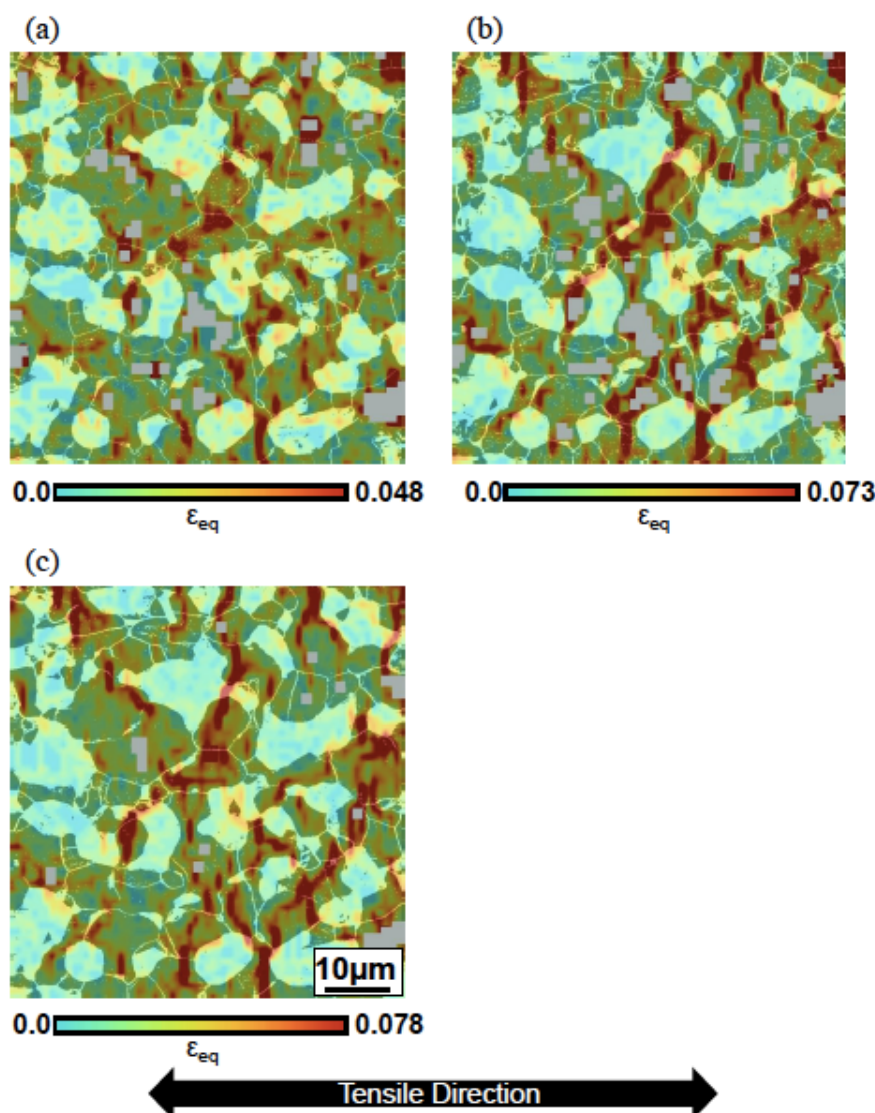


Figure 7. Local strain distribution maps obtained from the DIC analysis of the DP specimen having the isolated martensite morphology. The volume fraction of martensite (V_m) was 28%. The specimen was deformed to various tensile strains: (a) tensile tested to 1.1% strain; (c) 3.7%; (d) 6.4%.

Figure 8 shows frequency distributions of local equivalent strain within each phase in (a) the networked DP structure and (b) the isolated DP structure. The volume fraction of martensite (V_m) was 28% for both types of microstructures. As was shown in figures 6 and 7, local strains in the ferrite are larger than those in martensite in both types of DP structures, because of the strain localization in the softer ferrite. It is noteworthy, however, that the martensite in the networked DP structure has higher strain values (i.e., is more deformed) than the martensite in the isolated DP structure. Also, the distributions of local strain in both the ferrite and martensite phases in the networked DP structure are broader than those in the isolated DP structure. The results indicate that the degree of strain partitioning between soft ferrite and hard martensite decreases when the hard phase (martensite) has a connected network structures. That is, the deformation becomes more homogeneous in the networked DP structure than in the isolated DP structure, which must contribute to the better strength-ductility balance in the networked DP structure than in the isolated DP structure shown in figure 4.

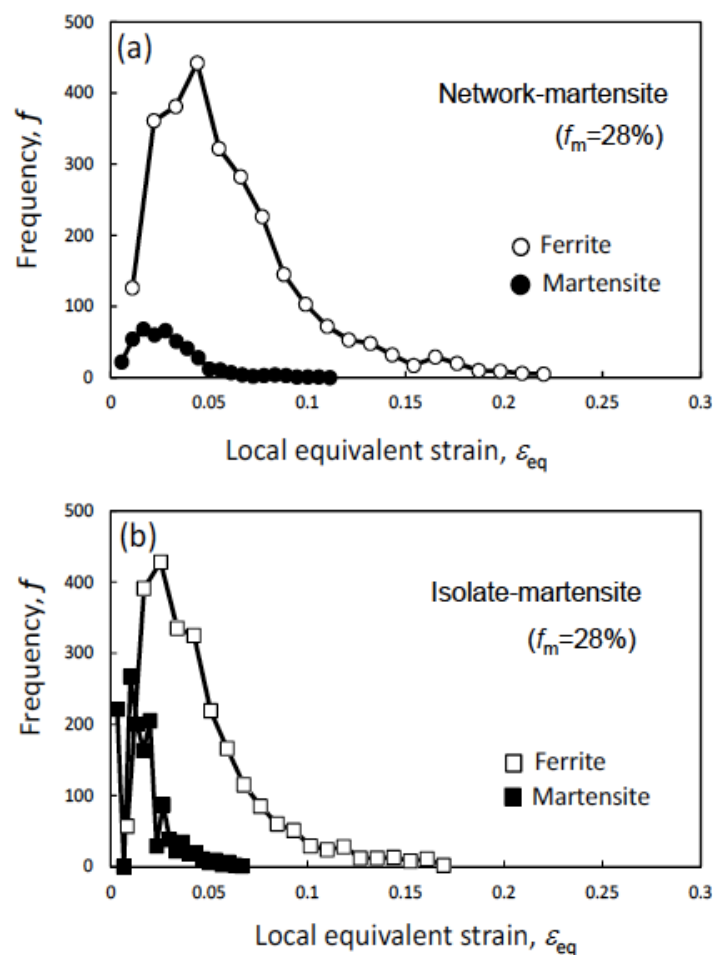


Figure 8. Frequency distribution of local strains in the DP specimens having (a) networked martensite morphology and (b) isolated martensite morphology. The volume fraction of martensite (F_m) was 28% for the both specimens.

4. Conclusion

Two types of dual phase (DP) microstructures, composed of a soft ferrite phase and a hard martensite phase, were fabricated in a low-carbon steel (Fe-0.087C-0.79Si-1.77Mn-0.009P-0.002S-0.02Cr-0.01Mo-0.003N in mass%) using two different types of heat treatment. When the starting microstructure prior to intercritical annealing in the ferrite + austenite two-phase region was ferrite, DP structures having a networked martensite were produced. In contrast, when the starting microstructure prior to intercritical annealing was austenite, DP structures with an isolated martensite morphology were obtained. Samples fabricated with these two types of DP structures, having various volume fractions of martensite, were tensile tested at room temperature. It was noteworthy that the DP structures with networked martensite showed a better strength-ductility balance than the DP structures with an isolated martensite morphology. The local strain distribution within the DP microstructures was quantitatively analyzed by digital image correlation (DIC) analysis during the tensile tests. The strain distributions within the DP microstructures were not homogeneous, but rather localized within soft ferrite grains. The strain-localized regions tended to detour around the hard martensite but eventually propagated across the martensite. It was found that the degree of strain partitioning between ferrite and martensite in the networked DP structure was lower than that in the isolated DP structure. That is, the deformation became more homogeneous when the hard phase (martensite) was connected to make a network structure. It is proposed that this is one of the reasons for the better strength-ductility balance in the networked DP structure compared to that in the isolated DP structure.

Acknowledgments

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